3Φ INDUCTION MACHINES

Problem #1) A 3Φ, 60 Hz, design B, 100 hp, squirrel cage induction motor has a rated operating speed of 870 rpm. Determine the **number of poles** of the machine.

 # poles = _____8_____ poles

Problem #2) Given a 4 pole, 50 hp, 1755 rpm, 460 V, 60 Hz, squirrel cage induction machine, determine the rated **Torque** of the machine in lb·ft.

T = _______149.6_______lb·ft

Problem #3) A 1 hp, 48 pole, 50 Hz, induction motor is operating at a speed of 120 rpm. Determine the **slip** at this speed.

s = ______4______%

Problem #4) Briefly describe the operational mechanism that causes an induction machine to develop no torque when operating at its synchronous speed.

The rotor conductors are rotating at the same speed of the stator field ⇒ no voltage is induced on the conductors.

Problem #5) Given a 3Φ, 40-hp, 460-V, 4-pole, 60 Hz, Y-connected, squirrel-cage, induction machine with the following characteristics: $R_S = 0.1\ \Omega$, $X_S = 0.4\ \Omega$, $R'_R = 0.15\ \Omega$, $X'_R = 0.6\ \Omega$, $R_{fe} = 102\ \Omega$, $X_m = 7.7\ \Omega$, $P_{mechlosses} = 1200$ W.
If the machine is operating at rated voltage and a slip of 2%, determine the **input current magnitude** and the **power on the shaft** of the machine.

$|I_{line}|$ = ________53.73________A

P_{shaft} = _______33.87________hp

Problem #6) Given a 6 pole, 50 hp, 1155 rpm, 460 V, 60 Hz, squirrel cage induction machine, determine the rated **Torque** of the machine in lb.-ft.

T_{rated} = ______227.36______lb·ft

Problem #7) A 1 hp, 48 pole, 50 Hz, induction motor is operating at a slip of 3.2%. Determine the **speed** of the machine.

n_r = _______121_______rpm

Problem #8) Given a 3Φ, 80-hp, 460-V, 4-pole, 60 Hz, Y-connected, squirrel-cage, induction machine with the following characteristics: $R_S = 0.2\ \Omega$, $X_S = 0.4\ \Omega$, $R'_R = 0.2\ \Omega$, $X'_R = 0.6\ \Omega$, $R_{fe} = 102\ \Omega$, $X_m = 7.7\ \Omega$.
If the machine is operating at 70% of rated load and a slip of 5%, determine the **total mechanical losses** of the machine.

$P_{mechlosses}$ = ______1361______W

Problem #9) A 3Φ, 60Hz, 50 hp, squirrel cage induction motor has a rated operating speed of 1165 rpm. Determine the **number of poles** of the machine.

 # poles = ____6____ poles

Problem #10) Given a 3Φ, 40-hp, 460-V, 4-pole, 60 Hz, Y-connected, squirrel-cage, induction machine with the following characteristics: $R_S = 0.15\ \Omega$, $X_S = 0.5\ \Omega$, $R'_R = 0.15\ \Omega$, $X'_R = 0.6\ \Omega$, $R_{fe} = 102\ \Omega$, $X_m = 7.7\ \Omega$.
If the machine is operating at rated voltage and a speed of 1728 rpm, determine the **torque** developed by the machine and the **input impedance** of the machine.

T_D = ______189.0______lb·ft

Z_{in} = ____2.475+j1.97____ Ω

Problem #11) Which Induction machine circuit-model **parameters** are determined from the **Blocked Rotor Test**? (Be specific – Do not assume that any other tests are also being performed on the machine.)

R_{eq}* and *X_{eq}

Problem #12) A ½-hp, 4-pole, 60-Hz, 1740-rpm induction motor is 74% efficient at rated load. Determine the **electrical input power** under rated conditions.

$$\text{For motor: }\ \eta = \frac{P_{out}}{P_{in}} = \frac{P_{shaft}}{P_{elec}} \quad \therefore \quad P_{elec} = \frac{P_{shaft}}{\eta} = \frac{\tfrac{1}{2}hp \cdot 746\left(\tfrac{W}{hp}\right)}{0.74} = 504$$

P_{in} = _____504_____W

Problem #14) A 3Φ, 60Hz, design B, 15-hp, squirrel cage induction motor has a rated speed of 700 rpm. Determine the **number of poles** of the machine.

 # poles = ____10____ poles

Problem #15) A 4 pole, 230V, 60Hz, induction motor is operating with a slip of 4%. Determine the **speed**.

n_r = _____1728_____rpm

Problem #16) Given a 3Φ, 40-hp, 460-V, 8-pole, 60 Hz, Y-connected, squirrel-cage, induction machine with the following characteristics: $R_s = 0.15\ \Omega$, $X_s = 0.5\ \Omega$, $R'_r = 0.2\ \Omega$, $X'_r = 0.5\ \Omega$, $R_{fe} = 102\ \Omega$, $X_m = 7.7\ \Omega$.
If the machine is operating at rated voltage and a speed of 885 rpm, determine the **torque** developed by the machine.

***Note:* $T_D = T_{mech}$**

T_D = _____133.64_____lb·ft

Problem #17) Given a 3Φ, 50-hp, 460V, 6-pole, 1142 rpm, 60Hz, squirrel-cage, induction machine: Determine the **rated torque** of the machine.

T_{rated} = ____229.95____lb-ft

Problem #19) A 12 pole, 50 Hz, induction motor is operating at a slip of 2%. Determine the machine's **speed**.

n_r = _______490_________rpm

Problem #20) Given a 3Φ, 40-hp, 460-V, 8-pole, 60 Hz, Y-connected, squirrel-cage, induction machine with the following characteristics: $R_s = 0.2\ \Omega$, $X_s = 0.5\ \Omega$, $R'_r = 0.16\ \Omega$, $X'_r = 0.6\ \Omega$, $R_{fe} = 100\ \Omega$, $X_m = 8\ \Omega$.
If the machine is operating at rated voltage and a speed of 880 rpm, determine the **magnitude of the line current** and the **developed (mechanical) torque** for the machine.

I_{line} = _________53.87_____________A

T_{mech} = ________212.93_________lb·ft

(Theory Questions Relating to Induction Machines)

Problem #21) Define the term ***synchronous speed*** with respect to induction machines.

i – the rotational speed of the stator field, *or*
ii – the speed at which the machine develops no torque

Problem #22) For each of the following statements, specify whether they are **TRUE** or **FALSE**.

___False___ A 3-Φ induction machine produces ***no developed torque at start-up*** (startup: $n_r = 0$).

___True___ A 3-Φ induction machine produces ***no mechanical power at start-up***.

___False___ The ***breakdown torque*** for a 3Φ induction machine is the maximum load torque that the machine is able to break-free and accelerate at start-up.

___True___ The ***no-load test*** for a 3Φ induction machine allows for solution of the excitation impedances in the equivalent circuit model.

___True___ The ***rated speed*** of a 3Φ induction machine is the speed the machine should run under full-rated conditions.

___True___ A 3Φ, squirrel-cage, induction machine requires ***no external electrical connection to the rotor***.

___True___ A 4-pole, 3Φ induction machine will have a ***higher synchronous speed*** when supplied by a 60Hz source compared to when being supplied by a 50Hz source.

___True___ A 3Φ induction machine produces ***no developed*** (mechanical) ***torque at synchronous speed***.

___True___ A 3Φ induction machine produces ***no torque*** and ***no mechanical power*** at synchronous speed.

___True___ The ***direction of rotation*** for a 3Φ induction machine depends on the phase sequence of the source.

___False___ At synchronous speed, a 3Φ induction machine will draw ***no line current*** ($I_{line} = 0A$).

___False___ The ***frequency of the rotor voltages*** in a 3Φ induction machine will increase as the machine accelerates from start-up to synchronous speed.

___True___ 1 ***horsepower*** is roughly equivalent to 746 watts of power.

___False___ A 3Φ induction machine functions as a ***generator when running backwards***.

___True___ The ***rated speed*** of a 3Φ induction machine is the speed the machine should run under full-rated conditions.

___False___ Increasing the ***rotor-circuit resistance*** of a 3Φ, wound-rotor induction machine will increase the speed at which maximum torque occurs.

___False___ When supplied at rated voltage, a 3Φ induction machine develops ***rated torque*** at its synchronous speed.

___False___ The “no-load” speed of an “ideal” 3Φ induction motor can be increased by increasing the ***magnitude*** of its supply voltage.

Problem #23) A 15hp, 230V, 1750rpm, DC shunt-motor has field and armature resistances of 140Ω and 0.3Ω respectively. If the motor draws a line current of 55A under full rated conditions, determine:

a) The full-voltage start-up terminal current if no external starting resistance is applied.

b) The full-voltage start-up terminal current if a 5Ω resistor is connected in series with the armature circuit.

a) $I_{start(R=0\Omega)}$ = __768.3___A

b) $I_{start(R=5\Omega)}$ = ___45.0___A

Problem #24) A 25hp, 240V, DC shunt-motor (R_f = 120Ω, R_a = 0.25Ω) draws 90A when supplied with rated voltage and driving ***rated load***. Determine the **mechanical losses** experienced by the motor.

$P_{mech.losses}$ = ____537____W

Problem #25) A 30hp, 240V, shunt-excited DC motor running at 900 rpm draws a line current of 90A when supplied at rated voltage and driving a constant-torque (***not-rated***) load. The respective field and armature resistances are 120Ω and 0.25Ω. Neglecting any mechanical losses in the machine:

a) Determine the **mechanical power** produced by the machine.

b) If a resistor is placed in series with the field winding that decreases the pole flux by 25%, determine the new operating **speed** of the motor.

a) P_{mech} = ____25.7____hp

b) n_{new} = ____1160____rpm

Problem #26) A 240V, shunt-excited DC motor running at 900 rpm draws a line current of 90A at rated voltage when supplied at rated voltage and driving a load. The respective field and armature resistances are 120Ω and 0.3Ω. Neglecting any mechanical losses in the machine:

a) Determine the **mechanical power** produced by the machine

b) If a change in the motor's mechanical load causes the input current to increase by 10%, determine the ***new mechanical power*** and the ***new speed*** of the motor.

a) P_{mech} = ________25.2________hp

b) P_{mech} = ________27.4________hp

n_{new} = ________888.6________rpm

Problem #27) A 240V, DC shunt-motor (R_f = 120Ω, R_a = 0.3Ω) draws 90A and rotates at 900rpm when driving a constant-torque (*non-rated*) load and supplied at rated voltage. If a 1Ω resistor is placed in series with the armature circuit, determine the ***new speed*** of the motor along with the ***mechanical power*** produced by the motor (with the resistor in place).

n_{new} = ________529________rpm

P_{mech} = ________14.8________hp

Problem #28) Given a 120V, ½hp, **series**-excited, DC motor with field resistance of 3.4Ω and an armature resistance of 2.6Ω; Assuming that the total pole flux created by the motor is linearly proportional to the motor's field current ($\Phi \equiv I_f$) and that the motor is supplied at rated voltage:

- **a)** If the motor draws a terminal current of 1.5A while rotating at a speed of 1600rpm, determine the total ***torque***, T_D, developed by the motor at this operating point.
- **b)** If the load torque increases such that the motor draws a 3x larger terminal current of 4.5A, determine the ***new operational speed*** and the ***new torque*** developed by the motor.

V_t = 120V (for parts "a" and "b")

Part "a"

It_{orig} = 1.5A	Ea_{orig} = 111V	$P_{mech(orig)}$ = 166.5W = 0.2232hp
T_{Dorig} = 0.7326lb.ft	$(k_G\Phi)_{orig}$ = 0.069375	

Part "b"

It_{new} = 4.5A	Ea_{new} = 93V	$P_{mech(new)}$ = 418.5W = 0.5610hp
$(k_G\Phi)_{new}$=0.208125	**n_{new} = 447rpm**	**T_{Dnew} = 6.594lb.ft**

a) T_D = **0.7326** lb·ft

b) $n_{(new)}$ = **447** rpm

$T_{D(new)}$ = **6.594** lb·ft

Problem #29) Given a 5hp, 1800rpm, 230V_{DC}, shunt-excited motor with circuit model resistances:

R_f=209Ω, R_a=1.5Ω (Assume $P_{mech.losses}$ = 0W)

- **a)** Determine the **rated torque**, $T_{shaft(rated)}$, for the motor in lb·ft.
- **b)** If the motor draws a terminal current of 14.3A while supplied with rated voltage but driving ***less-than-rated*** load, determine the **mechanical power**, P_{mech}, produced by the motor in horsepower and the operational **efficiency**, η, of the motor in percent.
- **c)** Determine the **starting current** for the motor if it is initially started by applying full (rated) terminal voltage. (Note – "starting" condition → n_r = 0 rpm)

(see last page for solution)

a) $T_{shaft(rated)}$ = **14.6** lb·ft

b) P_{mech} = **3.72** hp

η = **84.4** %

c) $I_{t(starting)}$ = **154.4** A

Problem #30) A 12V, permanent-magnet DC motor (no field winding) with an armature circuit resistance R_a = 4Ω is used to drive a radio-controlled car. The motor rotates at a speed of 2700rpm and draws a terminal current I_t = 300mA when the car is traveling on a smooth, level surface. Assuming that the motor is supplied at rated voltage:

- **a)** Determine the **torque** that the motor develops, T_D, in lb·ft when on the level surface.
- **b)** When the car begins traveling up a long incline, the car's speed decreases and the motor's terminal current increases to I_t = 500mA. Determine new **torque** developed by the motor, $T_{D(incline)}$, in lb·ft and the new rotational **speed** of the motor, $n_{r(incline)}$, in rpm.

(see last page for worked-out solution)

a) T_D = **0.0084448** lb·ft

b) $T_{D(Incline)}$ = **0.01408** lb·ft

$n_{new(Incline)}$ = **2500** rpm

Problem #31) Given a small 18V_{DC} permanent-magnet motor with armature circuit resistance R_a=2Ω; While the motor is supplied with rated voltage and driving a small load, the motor's speed was measured at 2670rpm and the terminal current was measured at 0.4A.

a) Determine the **torque**, $T_{D(2670)}$,developed by the motor while operating as specified above.
b) An increase in load torque causes the motor to slow down to 2150rpm while still supplied at rated voltage. Determine the **new terminal current**, $I_{t(2150)}$, and the **new torque**, $T_{D(2150)}$, developed by the motor while rotating at 2150rpm.
c) If the permanent magnets that provide the stator flux are swapped-out with rare-earth magnets that provide 2x more flux than the original magnets, determine the **new rotational speed** of the motor, n_r, assuming that the motor is developing the same torque as in part (b).

a) $T_{D(2670)} =$ **0.01814** lb·ft

b) $I_t =$ **2.075** A

$T_{D(2150)} =$ **0.0941** lb·ft

c) $n_r =$ **1236** rpm

Problem #32) Given the permanent-magnet motor from problem #31 (18V_{DC}, R_a=2Ω) supplied at 18V:
a) Determine the value of the **terminal current** that the motor will draw and the **torque** that the motor will develop at start-up with the original magnets in place.
b) Determine the value of the **terminal current** that the motor will draw and the **torque** that the motor will develop at start-up with the rare-earth magnets in place.

a) $I_t =$ **9** A

$T_D =$ **0.408** lb·ft

b) $I_t =$ **9** A

$T_D =$ **0.816** lb·ft

Problem #33) Write **True** or **False** in each blank based upon the validity of each statement:

___False___ A 3Φ induction machine develops no torque at start-up.

___True___ A 3Φ induction machine produces no mechanical power at start-up (when $n_r = 0$).

___False___ The breakdown torque for a 3Φ induction machine is the maximum torque load the machine is able to break-free and accelerate at start-up.

___True___ The rated speed of a 3Φ induction machine is the speed the machine should run under full-rated conditions.

___True___ A 3Φ, squirrel-cage, induction machine requires no external electrical connection to the rotor.

___True___ A 4-pole, 3Φ induction machine will have a higher synchronous speed when supplied by a 60Hz source compared to when being supplied by a 50Hz source.

___True___ A 3-Φ induction machine produces no torque or mechanical power at synchronous speed.

___True___ The direction of operation for a 3Φ induction machine depends on the phase sequence of the voltage source.

___False___ At synchronous speed, a practical 3Φ induction machine will draw no line current ($I_{line} = 0A$).

___True___ 1 horse power is roughly equivalent to 746 watts of power.

___False___ Increasing the field current in a shunt-excited DC motor will typically cause an increase in speed.

___False___ When supplied at rated voltage, a DC motor only produces a torque at its synchronous speed.

___False___ Although it can only consume reactive power, a DC machine can produce or consume real power.

___True___ DC machines require an external electrical connection to their rotor conductors.

___False___ Provided the breakdown torque is not reached, the speed of a DC motor is not dependent on supply voltage magnitude.

___True___ When supplied at full rated voltage, a DC machine will typically draw a "starting" current that is many times larger than its rated current.

___False___ The DC field winding of a DC machine is mounted on the rotor of the machine.

Problem #34) Multiple Choice – Choose the best response to complete each statement

__d__ The field winding of a shunt-excited DC Machine:

A) is designed to be connected in parallel with the armature
B) typically has a relatively large resistance in order to draw a relatively small current
C) can be connected in series with a variable external resistor to allow for speed control
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__c__ A DC motor:

a) only produces a torque at its synchronous speed
b) produces a torque at all speeds except its synchronous speed
c) does not have a synchronous speed
d) all of the above (a-c) are correct
e) none of the above (a-d) are correct

__e__ A series-excited DC motor:

a) produces no starting torque
b) generally produces less starting torque than an equivalent rated shunt motor
c) can only be self-started if an additional shunt field winding is also applied
d) all of the above (a-c) are correct
e) none of the above (a-d) are correct

__b__ Under normal operation of a DC motor, a decrease in load torque (with no other user supplied changes):

a) will cause the machine to slow down
b) will cause the machine to speed up
c) will not change the speed of the machine
d) all of the above (a-c) are correct
e) none of the above (a-d) are correct

__c__ At start-up with applied rated voltage, a shunt excited DC motor:

a) will draw a starting current equal to the machine's rated current
b) will draw a starting current less than the machine's rated current
c) will draw a starting current greater than the machine's rated current
d) all of the above (a-c) are correct
e) none of the above (a-d) are correct

Problem #35) Specify whether each statement is **True** or **False.**

___False___ A 3-Φ induction machine develops no torque when rotating faster than its synchronous speed ($n_r > n_s$).

___True___ A 3-Φ induction machine will function as a generator when rotating faster than its synchronous speed ($n_r > n_s$).

___False___ 1 lb·ft of torque is equivalent to 746 watts.

___True___ Under normal operation, decreasing the field current in a shunt-excited DC motor while maintaining constant terminal voltage will cause in the motor's speed to increase.

___False___ A DC machine will function as a generator if it pushed faster than its synchronous speed by an external mechanical source.

___False___ When supplied at rated voltage, a 3-Φ induction machine develops rated torque at its synchronous speed.

___False___ A DC machine utilizes a commutator and brushes to provide an external electrical connection to its stator (field) windings.

___False___ A permanent-magnet DC motor does not require an electrical connection to its armature.

___True___ The voltage "E_a" that appears in the circuit model of a DC machine only exists as a non-zero voltage when the rotor of the machine is rotating.

___False___ The "no-load" speed of an "ideal" 3Φ induction motor can be increased by increasing the magnitude of its supply voltage.

___True___ The "no-load" speed of an "ideal" shunt-excited DC motor can be increased by increasing the magnitude of its supply voltage.

Problem #36) Write the letter corresponding to the best response for each statement in the blank preceding the statement.

__**E**___ Given a motor that is supplied with rated voltage and is initially driving a load that requires rated torque, if the load is adjusted such that there is a ***50% decrease in the amount of torque required to drive the load***:

A) the motor will slow down
B) the motor will draw more current
C) the motor will eventually overheat because it is producing more torque than the load requires
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__**B**___ Given a ***DC motor*** that is initially operating normally, an ***increase in the load torque***

A) will cause the machine to speed up
B) will cause the machine to slow down
C) will not change the speed of the machine
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__**D**___ The ***relative permeability*** of a magnetic core:

A) must be greater than or equal to one (1)
B) will decrease if the core becomes saturated
C) would be infinite for an “ideal” magnetic core
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__**A**___ The ***Magneto-Motive Force*** (MMF) created by a DC current flowing in the source coil of a magnetic circuit:

A) is proportional to the current flowing in the coil
B) is proportional to the rate of change in the voltage applied across the source coil
C) may be increased by wrapping the coil around a physically larger magnetic core
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__**B**___ The ***field winding*** of a ***shunt-excited DC motor***:

A) can also be wired in series with the armature to turn the machine into a series-excited DC motor
B) typically has a “high” resistance in order to minimize the electrical power loss in the winding
C) requires brushes and a commutator to provide an electrical connection to the winding
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__**D**___ The effective ***turns-ratio*** of a transformer that is connected to its load in a “step-up” configuration:

A) will be less than one.
B) can be determined by dividing the primary winding’s rated voltage by the secondary winding’s rated voltage.
C) will be the inverse of the turns-ratio of the same transformer connected in a “step-down” configuration.
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__**C**___ At ***start-up*** with applied rated voltage and no external resistances, a ***motor*** will typically:

A) draw a starting current that is equal to the machine’s rated current
B) draw a starting current that is much less than the machine’s rated current
C) draw a starting current that is much greater than the machine’s rated current
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

__**C**___ Under normal operation, the ***series field winding*** of a ***DC motor***:

A) can have the number of its turns increased or decreased in order to control the speed of the motor
B) may be connected in series with an external, variable resistor to provide a method of speed control
C) will have the same current flowing through it that is flowing through the machine’s rotor windings
D) all of the above (a-c) are correct
E) none of the above (a-d) are correct

#29 Solution

a) $$T_{rated} = \frac{P_{rated} \cdot 5252}{n_{rated}} = \frac{5 \cdot 5252}{1800} = \underline{\underline{14.6}}\, lb \cdot ft$$

b) Shunt Excited Motor…

$$I_f = \frac{V_t}{R_f} = \frac{230}{209} = 1.10\, amps \quad \Rightarrow \quad I_a = I_t - I_f = 14.3 - 1.10 = 13.2\, amps$$

$$E_a = V_t - I_a \cdot R_a = 230 - (13.2) \cdot (1.5) = 210.2\, volts$$

$$P_{mech} = E_a \cdot I_a = (210.2) \cdot (13.2) = 2774.6\, watts \cdot (\tfrac{1hp}{746W}) = \underline{\underline{3.72}}\, hp$$

$$P_{elec} = V_t \cdot I_t = (230) \cdot (14.3) = 3289\, watts$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{mech}}{P_{elec}} = \frac{2774.6}{3289} = 0.8436 = \underline{\underline{84.36}}\%$$

c) At startup $E_a = 0\, rpm$ (I.e. – the source "E_a" looks like an ideal wire)…

$$I_f = \frac{V_t}{R_f} = \frac{230}{209} = 1.10\, amps \quad and \quad I_a = \frac{V_t}{R_a} = \frac{230}{1.5} = 153.33\, amps$$

$$I_t = I_f + I_a = 1.10 + 153.33 = 154.43\, amps$$

#30 Solution

a) Since Permanent Magnet, there will be no field winding...

$$E_a = V_a - I_a \cdot R_a = V_a - I_a \cdot R_a = 12 - (0.3) \cdot (4) = 10.8\, volts$$

$$P_{mech} = E_a \cdot I_a = (10.8) \cdot (0.3) = 3.24\, watts \cdot (\tfrac{1hp}{746W}) = 0.004343\, hp$$

$$T_D = \frac{P_{mech} \cdot 5252}{n_r} = \frac{0.004343 \cdot 5252}{2700} = \underline{\underline{0.008448}}\, lb \cdot ft$$

$$\Rightarrow \quad k_G \cdot \phi = \frac{E_a}{n_r} = \frac{10.8}{2700} = 0.004\, {}^{V}\!/_{rpm} \qquad k_M \cdot \phi = \frac{T_D}{I_a} = \frac{0.008448}{0.3} = 0.02816\, {}^{lb \cdot ft}\!/_{A}$$

b) Since Permanent Magnet, $\boldsymbol{\phi}$ will be constant for both parts… thus $\boldsymbol{k_G \cdot \phi}$ and $\boldsymbol{k_M \cdot \phi}$ will also be constant.

$$I_a = 0.5\, amps$$

$$E_a = V_a - I_a \cdot R_a = V_a - I_a \cdot R_a = 12 - (0.5) \cdot (4) = 10\, volts$$

$$\therefore$$

$$T_D = k_M \cdot \phi \cdot I_a = (0.02816) \cdot (0.5) = \underline{\underline{0.01408}}\, lb \cdot ft$$

$$n_r = \frac{E_a}{k_G \cdot \phi} = \frac{10}{0.004} = \underline{\underline{2500}}\, rpm$$